

# Higgs boson productions at LHC as a probe of different littlest Higgs models with T-parity

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## Abstract

Higgs boson productions at the LHC will serve as a sensitive probe of various little Higgs models. In this work we comparatively study two littlest Higgs models with different T-parity constructions through examining their effects in three production processes of the Higgs boson at the LHC, namely the productions of a single Higgs, a Higgs-pair, as well as a Higgs boson associated with a pair of top and anti-top quarks. The two models are characterized by predicting a top partner canceling the Higgs mass quadratic divergence contributed by the top quark with even and odd T-parity, respectively. We find that both models can alter the SM cross sections sizably and their corrections also differ significantly. Therefore, the Higgs boson productions at the LHC may shed some light on these two models or even distinguish them.

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## I. INTRODUCTION

Little Higgs theory [1] has been proposed as an interesting solution to the hierarchy problem. In such a theory the Higgs boson is a pseudo-Goldstone boson and its mass is protected by an approximate global symmetry and free from one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model [2] economically implements the idea of the little Higgs theory. Due to the tree-level mixing of heavy and light mass eigenstates, the electroweak precision tests can give strong constraints on the model [3], which would require raising the mass scale of the new particles to be much higher than TeV and thus reintroduce the fine-tuning in the Higgs potential [4]. To tackle this problem, a discrete symmetry called T-parity has been proposed [5], which forbids those tree-level contributions. In the pioneer version of such model (hereafter called model-I) [5], the T-parity is simply implemented by adding the T-parity images for the original top quark interaction to make the Lagrangian T-invariant. A characteristic prediction of this model is a T-even top partner which cancels the Higgs mass quadratic divergence contributed by the top quark. Since the heavy top partner is T-even, it can be singly produced at the LHC, which is a crucial phenomenology of this model.

An alternative implementation of T-parity has recently been proposed (hereafter called model-II) [6], where all new particles including the heavy top partner responsible for canceling the SM one-loop quadratic divergence are odd under T-parity. An obvious virtue of this model is that the spectrum of the third-generation quark sector is simplified [6]. Many studies of the collider phenomenology for model-I have been done [7]. However, the phenomenology of model-II is quite different from model-I [6], especially for the heavy top partner, which is T-odd and cannot be singly produced at the LHC.

To probe these models at the LHC, the Higgs boson production processes are ideal places. Firstly, these littlest Higgs models mainly alter the Higgs sector of the SM and thus the Higgs properties may deviate from the SM Higgs boson. Secondly, the Higgs boson is the most important target of the LHC experiment [8] and its various production channels will be explored at the LHC. In this work we choose three typical production processes of the Higgs boson at the LHC as a probe of these littlest Higgs models. The first one is the production of a single Higgs boson via gluon-gluon fusion, which is the dominant production mechanism at the LHC [9]. The second one is the Higgs-pair production, which is rare but very important

since it provides a way to probe the Higgs boson self-coupling [10]. The third process is the production of a Higgs boson in association with a pair of top quarks, which plays an important role in testing the Yukawa coupling [11]. These processes have been studied in model-I [12, 13, 14, 15], but not yet in model-II. In this work, we comparatively study the effects of both models in these three Higgs production processes.

This work is organized as follows. In Sec. II we recapitulate the fermion and top quark Yukawa sector of the models. Since model-I has been elucidated in detail in the literature, we focus on model-II. In Sec. III, we study the effects of these models in the productions of a single Higgs, a Higgs-pair and a Higgs boson in association with a top quark-pair at the LHC. Finally, we give our conclusion in Sec. IV.

## II. THE LITTLEST HIGGS MODELS WITH T-PARITY

The original littlest Higgs model [2] is based on a non-linear sigma model describing the spontaneous breaking of a global  $SU(5)$  down to a global  $SO(5)$  at an energy scale  $f \sim \mathcal{O}(TeV)$ . The vacuum expectation value (VEV) of an  $SU(5)$  symmetric tensor  $\Sigma$  is proportional to

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & \mathbb{1} \\ 0 & 1 & 0 \\ \mathbb{1} & 0 & 0 \end{pmatrix}, \quad (1)$$

where  $\mathbb{1}$  represents a unit  $2 \times 2$  matrix. The low energy dynamics of non-linear sigma is described in terms of the field

$$\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0 \quad (2)$$

with

$$\Pi(x) = \sum_{a=1}^{14} \pi^a(x) X^a, \quad (3)$$

where  $\pi^a(x)$  are the Goldstone particles corresponding to 14 broken generators  $X^a$  for the  $SU(5) \rightarrow SO(5)$  breaking.

In the pioneer version of littlest Higgs model with T-parity (model-I), the T-parity in the top quark sector is implemented by simply adding the T-parity images of the original interaction to make the Lagrangian T-invariant. Thus, the heavy top partner which cancels the Higgs mass quadratic divergence contributed by the top quark is T-even. There are

detailed descriptions of this model in the literature [5] and we do not discuss it in detail here. In the following, we recapitulate an alternative version of T-parity construction (model-II) [6].

In model-II for each generation of fermion (quark and lepton), we introduce two doublets  $q_1$  and  $q_2$ , which are embedded into the incomplete representations of  $SU(5)$  multiplets  $Q_1$  and  $Q_2$ , and a right-handed  $SO(5)$  multiplet  $\Psi_R$  which transforms nonlinearly under the full  $SU(5)$ . The field content can be expressed as

$$Q_1 = \begin{pmatrix} q_1 \\ 0 \\ 0 \end{pmatrix}, \quad Q_2 = \begin{pmatrix} 0 \\ 0 \\ q_2 \end{pmatrix}, \quad \Psi_R = \begin{pmatrix} \psi_R \\ \chi_R \\ \tilde{\psi}_R \end{pmatrix}, \quad (4)$$

where  $q_A = (-id_{LA}, iu_{LA})^T$  with  $A = 1, 2$ , and  $\psi_R = (-id'_R, iu'_R)^T$ . The first component of the  $\tilde{\psi}_R$  is irrelevant to our study (as shown later), and the second component of the  $\tilde{\psi}_R$  is  $iq_R$ . The mirror fermions can be given  $\mathcal{O}(f)$  masses via a mass term [6],

$$\mathcal{L}_\kappa = -\kappa_{ij} f (\bar{Q}_1^i \xi - \bar{Q}_2^i \Sigma_0 \Omega \xi^\dagger) \Psi_R^j + h.c., \quad (5)$$

where  $\xi = e^{i\Pi/f}$ ,  $\Omega \equiv \text{diag}(1, 1, -1, 1, 1)$ , and  $i, j = 1, 2, 3$  are the generation indices. For simplicity, we assume the flavor diagonal and universal  $\kappa$  in the study.

They transform under the  $SU(5)$  as

$$Q_1 \rightarrow V Q_1, \quad Q_2 \rightarrow V^* Q_2, \quad \Psi_R \rightarrow U \Psi_R, \quad \xi \rightarrow V \xi U^\dagger, \quad \Sigma \rightarrow V \Sigma V^T, \quad (6)$$

here  $V$  is an  $SU(5)$  rotation matrix, and  $U$  is the unbroken  $SO(5)$  rotation and is a non-linear representation of the  $SU(5)$ . Under T-parity, the transformation laws are defined as

$$Q_1 \leftrightarrow \Sigma_0 Q_2, \quad \Psi_R \rightarrow -\Omega \Psi_R, \quad \xi \rightarrow \Omega \xi^\dagger \Omega. \quad (7)$$

Thus  $q_1 \leftrightarrow q_2$ , and  $\Sigma \rightarrow \tilde{\Sigma} = \Sigma_0 \Omega \Sigma^\dagger \Omega \Sigma_0$  under T-parity. Following the above transformation, the Lagrangian is T-invariant.

The Lagrangian in Eq. (5) contains the new Higgs boson interactions and the mass terms. For the first and second generations,

$$\mathcal{L}_\kappa \simeq -\sqrt{2}\kappa f \left[ \bar{d}_{L-} d'_{R-} + \frac{1+c_\xi}{2} \bar{u}_{L-} u'_{R-} - \frac{1-c_\xi}{2} \bar{u}_{L-} q_R + \frac{s_\xi}{\sqrt{2}} \bar{u}_{L+} \chi_R \right] + h.c., \quad (8)$$

where we ignored the generation indices, and  $c_\xi (\equiv \cos \frac{v+h}{\sqrt{2}f})$  and  $s_\xi (\equiv \sin \frac{v+h}{\sqrt{2}f})$  come from the non-linear sigma model field  $\xi$ , with  $h$  and  $v$  being the neutral Higgs boson field and its VEV, respectively. The fermion  $u_{L-} = (u_{L1} - u_{L2})/\sqrt{2}$  is T-odd, which together with  $u'_R$  gets a mass, and  $u_{L+} = (u_{L1} + u_{L2})/\sqrt{2}$  is T-even and massless. The same definition also applies to the down-type quarks. The fields  $q_R$  and  $\chi_R$  can be given large Dirac masses by introducing additional fields, as described in detail in [5]. We will simply assume that their masses are  $5f$ . From the above Eq. (8), we can see the the first component of the doublet  $\tilde{\psi}_R$  doesn't appear and the T-odd down-type quarks have no tree-level coupling with Higgs boson.

For the top quark sector, in order to cancel the quadratic divergence of the Higgs mass induced by top quark, it requires the introduction of the additional singlets as follows:  $Q_1 = (q_1, U_{L1}, 0_2)^T$  and  $Q_2 = (0_2, U_{L2}, q_2)^T$ . From Eq. (5) we can get the Higgs boson interactions and the mass terms for the third generation fermions

$$\begin{aligned} \mathcal{L}_\kappa \simeq & -\sqrt{2}\kappa f [\bar{d}_{L-} d'_R + \frac{1+c_\xi}{2} \bar{u}_{L-} u'_R - \frac{1-c_\xi}{2} \bar{u}_{L-} q_R - \frac{s_\xi}{\sqrt{2}} \bar{U}_{L-} q_R - \frac{s_\xi}{\sqrt{2}} \bar{U}_{L-} u'_R \\ & + \frac{s_\xi}{\sqrt{2}} \bar{u}_{L+} \chi_R + c_\xi \bar{U}_{L+} \chi_R] + \text{h.c.}, \end{aligned} \quad (9)$$

where the T-parity eigenstates are defined as  $U_{L+} = (U_{L1} + U_{L2})/\sqrt{2}$  (T-even), and  $U_{L-} = (U_{L1} - U_{L2})/\sqrt{2}$  (T-odd). The  $U_{L+}$  together with  $\chi_R$  gets a Dirac mass.

Introducing additional singlets  $U_1^c \leftrightarrow U_2^c$  under T-parity, the top quark Yukawa coupling can be written as [6]

$$\mathcal{L}_t = -\frac{\lambda}{2} f \epsilon_{ijk} \epsilon_{xy} \left[ (Q_1)_i \Sigma_{jx} \Sigma_{ky} U_1^c + (\Sigma_0 Q_2)_i \tilde{\Sigma}_{jx} \tilde{\Sigma}_{ky} U_2^c \right] + \text{h.c.}, \quad (10)$$

where the indices  $i, j, k$  run from 1 to 3 whereas  $x, y=4, 5$ . The Eq. (10) will introduce mixing between the light T-even and the heavy T-even fermions, which can be removed by the additional interactions [6],

$$\mathcal{L}'_t = -\frac{\lambda'}{2} f \epsilon_{lmn} \epsilon_{rs} \left[ (\Omega Q_2)_l \Sigma'_{mr} \Sigma'_{ns} U_1^c + (\Omega \Sigma_0 Q_1)_l \tilde{\Sigma}'_{mr} \tilde{\Sigma}'_{ns} U_2^c \right] + \text{h.c.}, \quad (11)$$

where the indices  $l, m, n$  run from 3 to 5 whereas  $r, s=1, 2$ .  $\Sigma' = \Omega \Sigma^\dagger \Omega$ , and  $\Sigma' \rightarrow \tilde{\Sigma}' = \Sigma_0 \Sigma \Sigma_0$  under T-parity. Adding  $\mathcal{L}'_t$  to  $\mathcal{L}_t$ , and taking  $\lambda' = \lambda$ , we can get the following simple expression of top quark Yukawa sector,

$$\mathcal{L}_t + \mathcal{L}'_t \simeq -\lambda f \left( \sqrt{2} s_\Sigma u_{L+} U_+^c + (1 + c_\Sigma) U_{L-} U_-^c \right) + \text{h.c.}, \quad (12)$$

where  $c_\Sigma(\equiv \cos \frac{\sqrt{2}(v+h)}{f})$  and  $s_\Sigma(\equiv \sin \frac{\sqrt{2}(v+h)}{f})$  are originated from the non-linear sigma model field  $\Sigma$ , and  $U_+^c = (U_1^c + U_2^c)/\sqrt{2}$ ,  $U_-^c = (U_1^c - U_2^c)/\sqrt{2}$ .

The Yukawa couplings of up-type quarks for the first and second generations are given by the similar Lagrangian for the top quark, but without introducing extra singlet fields,

$$\mathcal{L}_u = -\frac{\lambda_u}{2} f \epsilon_{ijk} \epsilon_{xy} \left[ (Q_1)_i \Sigma_{jx} \Sigma_{ky} u^c + (\Sigma_0 Q_2)_i \tilde{\Sigma}_{jx} \tilde{\Sigma}_{ky} u^c \right] + \text{h.c.}, \quad (13)$$

where  $u^c \rightarrow u^c$  under T-parity. The Eq. (13) contains the following Higgs boson interactions as well as the mass term for up-type quarks of the first and second generations,

$$\mathcal{L}_u \simeq -\lambda_u f s_\Sigma u_{L+} u^c + \text{h.c.}. \quad (14)$$

After diagonalizing the mass matrix Eq. (8, 9, 12, 14), we can get the mass eigenstates of new fermions. For each SM fermion doublet, there are  $d_-$ ,  $u_-$ ,  $q$  (T-odd), and  $\chi$  (T-even). Besides, the top quark has a T-odd partner  $T_-$  which cancels the one loop quadratic divergence of Higgs mass induced by top quark.

### III. THE EFFECTS IN HIGGS BOSON PRODUCTIONS AT THE LHC

The relevant Feynman rules in our calculations can be obtained after diagonalizing the mass matrix in Eqs. (8, 9, 12, 14), which is performed numerically in our analyses. The Higgs mass is assumed to be 150 GeV and other SM parameters involved are taken as  $m_t = 172.7$  GeV,  $m_Z = 91.187$  GeV [16], and we use the two-loop running coupling constant  $\alpha_s(Q)$  with  $\alpha_s(m_Z) = 0.118$ . For the parton distributions we use CTEQ6L [17] with the renormalization scale  $\mu_R$  and the factorization scale  $\mu_F$  chosen to be  $\mu_R = \mu_F = m_h$  for single Higgs production and  $\mu_R = \mu_F = 2m_h$  for Higgs-pair production. To simplify the top quark Yukawa sector, we have taken Yukawa coupling constants  $\lambda' = \lambda$ . Therefore, the new free parameters involved are the breaking scale  $f$  and  $\kappa$ . Our calculations show that the results are not very sensitive to  $\kappa$  in the allowed parameter space. Thus, we take  $\kappa = 3.0$ , and retain only  $f$  as free parameter. The [18] shows that the scale  $f$  in model-I may be below 1 TeV, and the constraint in model-II is expected to be even weaker [6].

Our calculations will deal with loop diagrams. The calculations of such loop diagrams are straightforward. Each loop diagram is composed of some scalar loop functions [19] which are calculated by using LOOPTOOLS [20]. Since the explicit expressions of these form factors are lengthy, we will not present them in the paper.

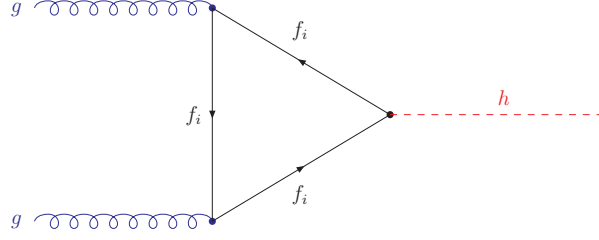


FIG. 1: The main parton-level Feynman diagrams for single Higgs boson production via gluon-gluon fusion in model-II. Here,  $f_i=t, \chi, T_-, u_-, q$  for the third generation, and  $f_i=\chi, u_-, q$  for the first two generations.

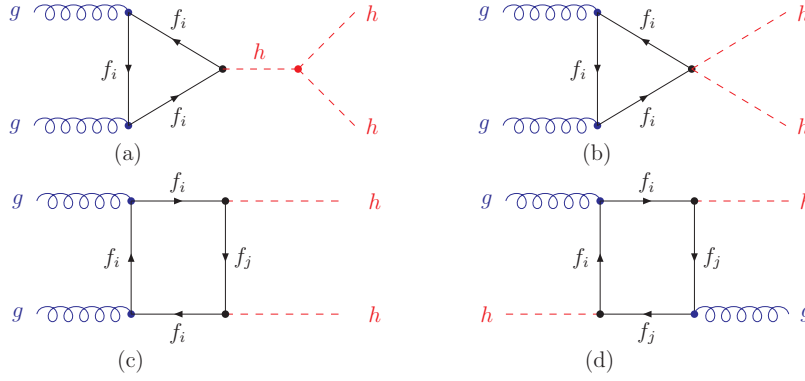


FIG. 2: The parton-level Feynman diagrams for Higgs-pair production via gluon-gluon fusion in model-II. Here,  $f_i$  can be a T-even quark ( $i = 1, 2$  with  $f_1 = u$  and  $f_2 = \chi$  for three generations) or a T-odd quark (for the third generation,  $i = 1, 2, 3$  with  $f_1 = T_-, f_2 = u_-$  and  $f_3 = q$ ; while for the first and second generations,  $i = 1, 2$  with  $f_1 = u_-$  and  $f_2 = q$ ). The other diagrams obtained by exchanging the two gluons or exchanging the two Higgs bosons are not shown here.

At the LHC the single Higgs production via gluon-gluon fusion is dominated by top quark loop in the SM. In model-II, the Feynman diagrams of the process are shown in Fig. 1. Due to the modified  $ht\bar{t}$  coupling, the top quark loop may give some corrections to SM prediction. In addition to the top quark loop, the loops of new T-even and T-odd quarks also come into play. In model-I the corrections are also mainly from these two aspects. The relevant Feynman diagrams and rules are described in detail in [12].

The Higgs-pair production at the LHC can proceed through gluon-gluon fusion and  $b\bar{b}$  annihilation at parton level, with the former being the dominant one [21]. The main Feynman diagrams of the process  $gg \rightarrow hh$  in model-II are shown in Fig. 2. In the SM the dominant contributions are from the diagrams in Fig. 2 (a, c, d) with top-quark running in the loops.

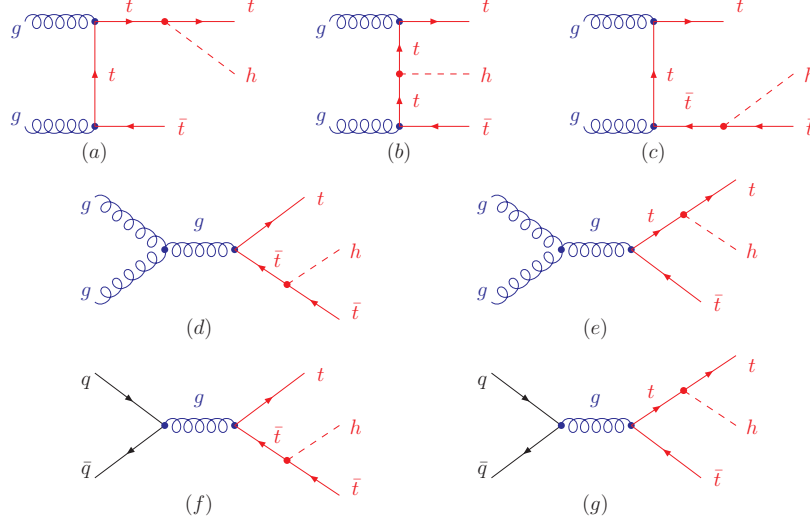


FIG. 3: The patron-level Feynman diagrams for  $ht\bar{t}$  production at the LHC in model-II. The u-channel diagrams by exchanging the two gluons in (a)-(c) are not shown here.

In model-II the top quark can give the new correction through the tree-level  $hht\bar{t}$  coupling and the modified  $ht\bar{t}$  coupling. Also, since the Higgs boson interacts with the T-even and T-odd quarks introduced, we have additional diagrams with these new quarks running in the loops. In model-I the diagrams of the corrections are similar, which are presented in [14]. In our calculation, we ignore the contributions of the light quark loops.

The production of  $ht\bar{t}$  at the LHC can proceed through  $gg$  fusion and  $q\bar{q}$  annihilation at parton level. In both model-II and model-I, the tree-level Feynman diagrams are the same as in the SM, which are shown in Fig. 3. The corrections are mainly from the modified  $ht\bar{t}$  coupling.

In Figs. 4-6 we plot the corrections to the SM predictions of the production rates versus the parameter  $f$ . In model-I we take  $r = 1.0$  and our results agree with [12, 14, 15].

Figs. 4-6 show that the contributions of these two models can significantly alter the SM cross sections in the allowed parameter space. The corrections are sensitive to the scale  $f$  and the magnitude becomes more sizable for lower values of  $f$ . Furthermore, we see the corrections in model-II are much more sizable than model-I. For example, for model-II (model-I) the correction is -43% (-25%) with  $f = 800$  GeV in Fig. 4, 41% (19%) with  $f=1$ TeV in Fig. 5, and -30%(-13.5%) with  $f = 600$  GeV in Fig. 6.



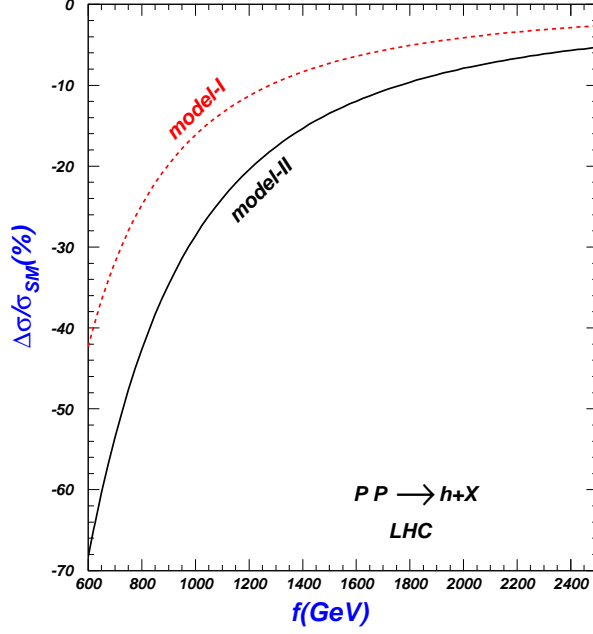


FIG. 4: The corrections to the SM single Higgs boson production rate versus the parameter  $f$  at the LHC.

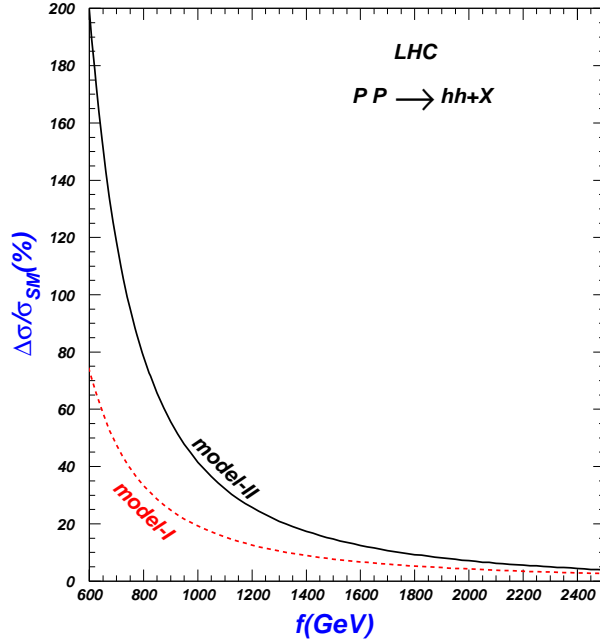


FIG. 5: The corrections to the SM Higgs-pair production rate versus the parameter  $f$  at the LHC.

#### IV. CONCLUSION

In this work we comparatively studied two typical littlest Higgs models with different T-parity constructions through examining their effects in three production processes of the Higgs boson at the LHC, namely the productions of a single Higgs, a Higgs-pair, as well

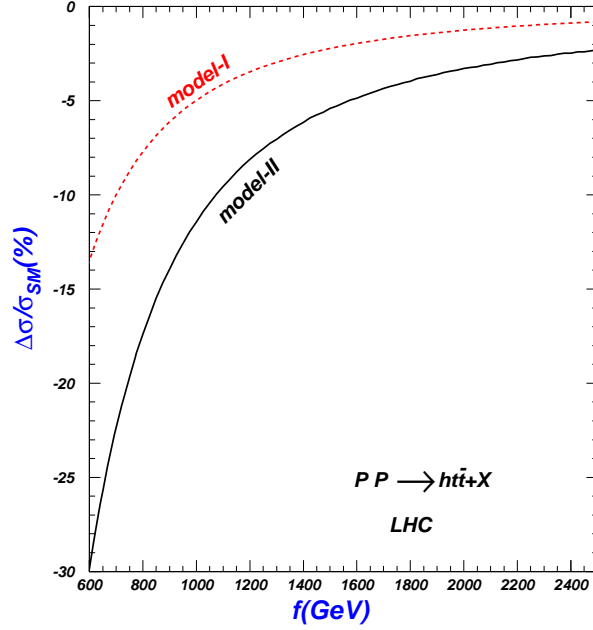


FIG. 6: The corrections to the SM  $ht\bar{t}$  production rate versus the parameter  $f$  at the LHC.

as a Higgs boson associated with a pair of top and anti-top quarks. We found that both models can alter the SM cross sections sizably and their corrections also differ significantly. Therefore, the Higgs boson productions at the LHC may shed some light on these two models or even distinguish them.

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